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INFLUENCE OF ELASTICITY ON THE LIFTING FORCE OF A WING,(U)

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by

B. S. Berkovs'kiy

FOREIGN TECHNOLOGY DIVISION

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Influence of Elasticity on the Lifting Force of a Wing
B. S. Berkovs'kiy

A deformable lifting surface presents interest from the point of view of consideration of rigidity of construction /1/ and of the obtaining of controlled aerodynamic characteristics.

In the paper there is investigated the problem of static aerohydroelasticity. The general equation of a lifting surface in an ideal incompressible unrestricted flow is examined. The elastic-deformable surface is studied under the assumptions of the high-aspect-ratio wing theory. There is obtained an integro-differential equation of the elastic wing. The solution of this equation yields the relationship for the lift coefficient of the undeformed wing and for the function of the effect of elasticity.

1. Let us examine the steady-state motion of a deformable lifting surface S with the velocity V_0 in an ideal incompressible unrestricted fluid at the small local angles $\alpha(y)$. We shall introduce the right-handed system of coordinates XYZ. The X-axis is directed to the right in the direction of motion, the Z-axis is directed vertically upward.

In the general case in terms of the acceleration potential the boundary value problem for the lifting surface is formulated as follows /2/:

$$\Delta\Theta=0 \quad Q\in\Omega, \quad \Theta_z=F(q_1)\ q,q_1\in S, \quad \Theta_- - \Theta_+ = 0 \quad q\in L, \qquad (1)$$

where Q, q, q_1 are points of the space $R^3, \Omega\in R^3\setminus S$. $F(q_1)$ is the function of the shape of the surface, L is the trailing edge, $q = q(\xi,\eta,\zeta)$, $q_1 = q_1(x,y,z)$.

In the case of a thin surface the acceleration potential is defined as the potential of a double layer:

$$\Theta=\frac{V_0}{4\pi}\iint_s \gamma(q)\frac{\partial}{\partial\zeta}\frac{1}{r}\,ds$$

where $r=\sqrt{(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2}$.

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Moving on to the velocity potential in a linear formulation, we shall define the latter on the basis of the coupling equation $\Theta = -V_0\varphi_x$:

$$\varphi = -\frac{1}{4\pi}\iint_s \gamma(q)\int_\infty^x \frac{\partial}{\partial\zeta}\frac{1}{r}\,d\tau\,ds$$

and with the aid of the boundary condition (1) we shall obtain the integral equation of the problem

$$\frac{1}{4\pi}\frac{\partial}{\partial y}\iint_s \frac{\gamma(q)}{y-\eta}\left[1-\frac{\sqrt{(x-\xi)^2+(y-\eta)^2}}{x-\xi}\right]ds = V_0 f_x(q_1). \qquad (2)$$

Here $f_x(q_1)$ is the derivative of the function of the shape of the surface.

In the case of a deformed lifting surface, assuming the displacements are small, we set

$$f(q_1) = f_0(q_1) + f_1(q_1),$$

where $f_0(q_1)$ is the function of the shape of the undeformed lifting surface; $f_1(q_1)$ is the sag due to load.

We shall define deformations at the point with the coordinates x, y, z from the load at the point ξ, η, ζ as a result of linearity as /3/

$$f_1(x, y) = \iint_s C(x, y, \xi, \eta)\cdot p(\xi, \eta)\,d\xi d\eta,$$

where $C(x,y,\xi,\eta)$ is a bivariate function of the effect that is the sag at the point with the coordinates x,y as a result of the action of the unit force applied at the point ξ, η, $p(q) = A_0\gamma(q)$, $A_0 = \varrho V_0^2$.

Then the general equation of the deformed surface will have the form

$$\frac{1}{4\pi}\frac{\partial}{\partial y}\iint_s \frac{\gamma(q)}{y-\eta}\left[1-\frac{\sqrt{(x-\xi)^2+(y-\eta)^2}}{x-\xi}\right]ds =$$

$$= V_0\left[f_{0x}(q_1) + A_0\iint_s C_x(x, y, \xi, \eta)\cdot\gamma(\xi, \eta)\,d\xi d\eta\right]. \qquad (3)$$

The analytic and numerical solution of the obtained bivariate integral equation (3) present certain difficulties. It is therefore reasonable, limiting the shapes in the plane, to carry out the preliminary investigations under assumptions of the theory of *high-, low-,* and arbitrary-aspect-ratio wings.

2. Let us examine the case of a *high*-aspect-ratio wing. Toward this end we shall carry out a number of transformations; we introduce the well-known approximation $\sqrt{(x-\xi)^2+(y-\eta)^2}\approx|y-\eta|$ and we set $\gamma(\xi,\eta)=\gamma(\xi)\cdot\gamma(\eta)$ for the case of a *rectangular* wing with the system of coordinates situated in the center of the plane S_p of the projection of S on the plane XOY. As a result of this we obtain the integrodifferential equation of the elastic wing with respect to circulation $\Gamma(y)=\int_{-a}^{a}\gamma(\xi)\gamma(y)\,d\xi$, assuming that

$$\gamma(\xi)=B\sqrt{\frac{a+\xi}{a-\xi}}:$$

$$\Gamma(y)=2\pi aV_0\left[\alpha_0-\frac{1}{4\pi V_0}\int_{-b}^{b}\frac{\Gamma\eta(\eta)\,d\eta}{y-\eta}+\right.$$

$$\left.+\frac{A_0}{\pi a}\int_{-b}^{b}\Gamma(\eta)\frac{\int_{-a}^{a}\sqrt{\frac{a-x}{a+x}}\int_{-a}^{a}\sqrt{\frac{a+\xi}{a-\xi}}C_x(x,\xi)\,d\xi\,dx}{\int_{-a}^{a}\sqrt{\frac{a+\xi}{a-\xi}}\,d\xi}\,d\eta.\right. \tag{4}$$

Here $2a = k$ is the chord, $2b = l$ is the span, $C_x(x,\xi)$ are the derivatives of the function of flexibility with properties analogous to the properties of the function of influence in the plane problem /4/.

In the general case the longitudinal and lateral elastic axes of the lifting surface can occupy an arbitrary position in S. The position of the projections of the lateral elastic axis in the middle of the region S_p does not introduce complications and the investigation can be conducted by examining the closed system of lifting surfaces analogously to the bivariate

case /4/. The introduction of the longitudinal elastic axis, which corresponds, for example, to the setting of the wing on the fuselage, requires additional constructions of the functions of influence and in the case of a high-aspect-ratio wing imposes certain limitations connected with the hypothese of plane sections.

Let us examine the case of the location of the lateral elastic axis on the leading (a) or on the trailing (-a) edges of the wing. In this case /4/:

$$x > \xi \quad C_x'(x,\xi) = \operatorname{sign} R \frac{1}{EI_y}\left[\left(x\xi - \frac{x^2}{2}\right) - \left(a\xi - \frac{a^2}{2}\right)\right],$$

$$x < \xi \quad C_x'(x,\xi) = \operatorname{sign} R \frac{1}{EI_y}\left(\frac{\xi^2}{2} - a\xi + \frac{a^2}{2}\right),$$

where sign R = +1 -- the setting on the leading edge,
-1 -- the setting on the trailing edge,

EI_y is the bending stiffness, in the general case it is variable according to the span.

If we set EI_y = constant, after additional transformations and the introduction of the dimensionless coordinates $x = \bar{x}a$, $y = \bar{y}b$ and the dimensionless circulation $\Gamma = 2\bar{\Gamma} b V_0$, we obtain (4) in the form of Prandtel's equation

$$\bar{\Gamma}(\bar{y}) = \frac{a_\infty}{2\lambda}\left[\alpha - \frac{1}{2\pi}\int_{-1}^{+1}\frac{\bar{\Gamma}\eta(\bar{\eta})\,d\bar{\eta}}{\bar{y}-\bar{\eta}}\right], \tag{5}$$

where $a_\infty = \frac{\partial C_y}{\partial \alpha}$, $\lambda = \frac{b}{a}$, $\alpha = \alpha_0 + \alpha_д$, $\alpha_д = \operatorname{sign} R \frac{A_1 \cdot H \cdot C_{y_д}}{\pi^2}$ - is the variable angle of attack; $H = \rho V_0^2 k^3 l/8EI_y$ is the similarity parameter of the statically aerohydroelastic lifting surfaces, $A_1 \approx 0.75$, and

$$C_{y_д} = \lambda \int_{-1}^{+1} \bar{\Gamma}(\bar{\eta})\,d\bar{\eta} \tag{6}$$

is the lift coefficient of the deformed wing. Thus,

$$\alpha_д \approx \operatorname{sign} R \frac{0{,}75 H C_{y_д}}{\pi} \tag{7}$$

3. We seek the solution of equation (5) in the form

$$\bar{\Gamma}(\bar{y}) = \alpha A_2 \Gamma_0(\bar{y}), \tag{8}$$

where $\Gamma_0(\bar{y}) = \sqrt{1-\bar{y}^2}$.

Introducing (8) into (5), we obtain an equation for the constant A_2, integrating which with respect to the span we have

$$A_2 = \frac{\frac{2}{\lambda}}{\frac{1}{2}+\frac{1}{\lambda}}. \tag{9}$$

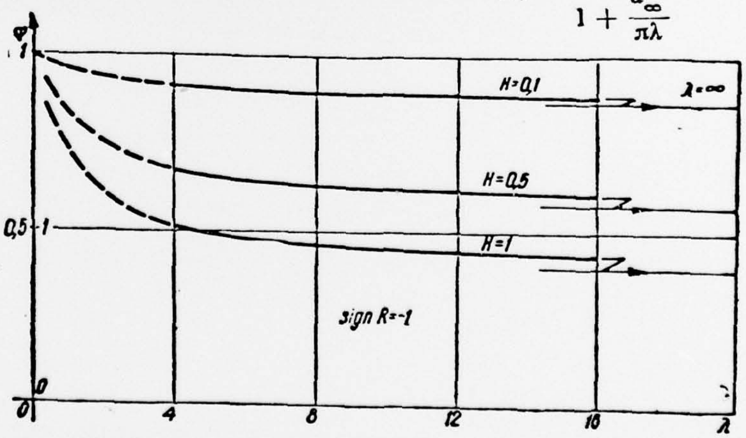
Taking advantage of (7)-(9), we obtain the equation for $C_{y_\text{д}}$:

$$C_{y_\text{д}} = \frac{\pi\lambda}{2} A_2 \alpha, \tag{10}$$

whose solution yields

$$C_{y_\text{д}} = \frac{C_{y_\text{нд}}}{1 - \operatorname{sign} R \dfrac{0.75H}{\frac{1}{2}+\frac{1}{\lambda}}} \tag{11}$$

where $C_{y_{н\alpha}} = 2\pi a_0/(1 + 2/\lambda)$ is the lift coefficient of the non-deformed high-aspect-ratio wing. Actually, $C_{y_\text{нд}} = \dfrac{a_\infty a_0}{1+\dfrac{a_\infty}{\pi\lambda}}$.



Setting

$$C_{y_\text{д}} = C_{y_\text{нд}} \cdot \psi, \tag{12}$$

we obtain the function of the influence of elasticity in the form

$$\psi = \frac{1}{1 - \operatorname{sign} R \dfrac{0{,}75H}{\dfrac{1}{2} + \dfrac{1}{\lambda}}}, \qquad (13)$$

which gives in the boundary cases

$$\lambda \to \infty \quad \psi \to \psi_0 = \frac{1}{1 - \operatorname{sign} R \cdot 1{,}5H}, \qquad (14)$$

$$\lambda \to 0 \quad \psi \to 1. \qquad (15)$$

Result (14) was obtained in work /4/, and result (15) shows that for the examined type of wing formally when $\lambda \to 0$ in the case sign R = -1 there exists a tendency to the absence of the influence of elasticity; when sign R = +1, the lift will be determined by the local angles of attack, the magnitudes of which, because of the assumptions of linearity, restrict the applicability of a result of type (13). To illustrate the obtained results there were carried out calculations according to formula (13) (figure), analysis of which shows that elasticity and aspect ratio together can significantly change the lift of the wing.

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